Verification of Small Hole Theory for Application To Wire Chaffing Resulting in Shield Faults

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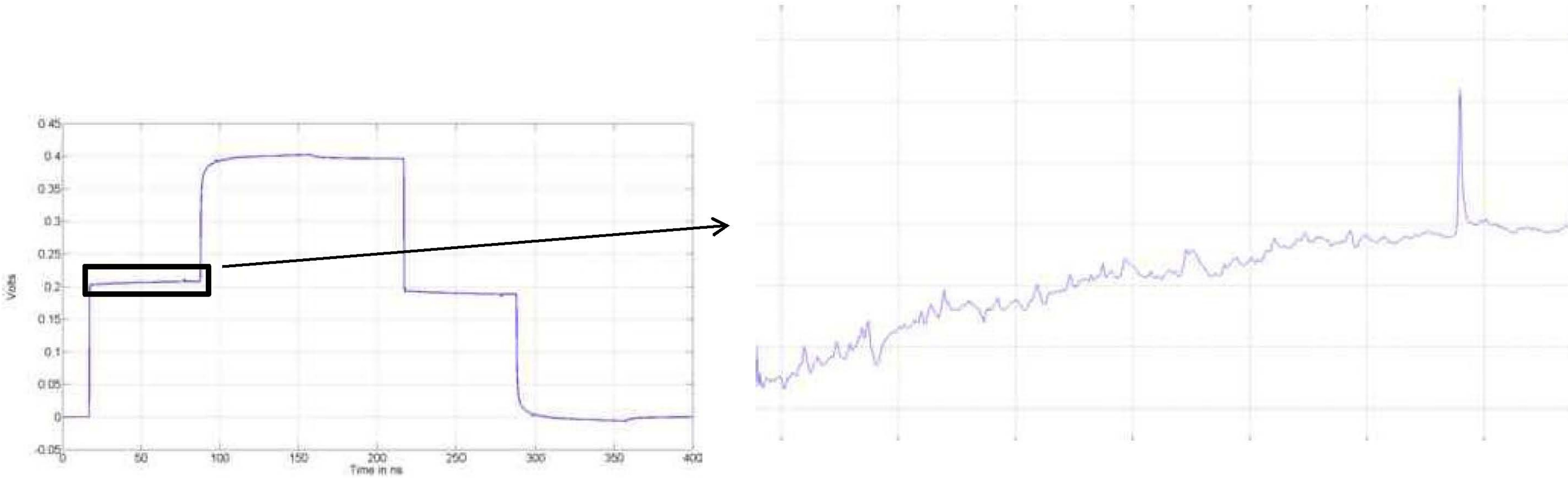
Problem Statement

- Want to identify wire chafing as early as possible by detecting holes in shielding.
- Developing coaxial cable approach first then shielded twisted pair.
- Developed physics based model of fields in hole of shielding in coax.
- This presentation provides validation of theoretical model via commercial software simulations.

What is the “noise” in wire fault detection?

Even perfect coaxial cable has “the wiggles”.

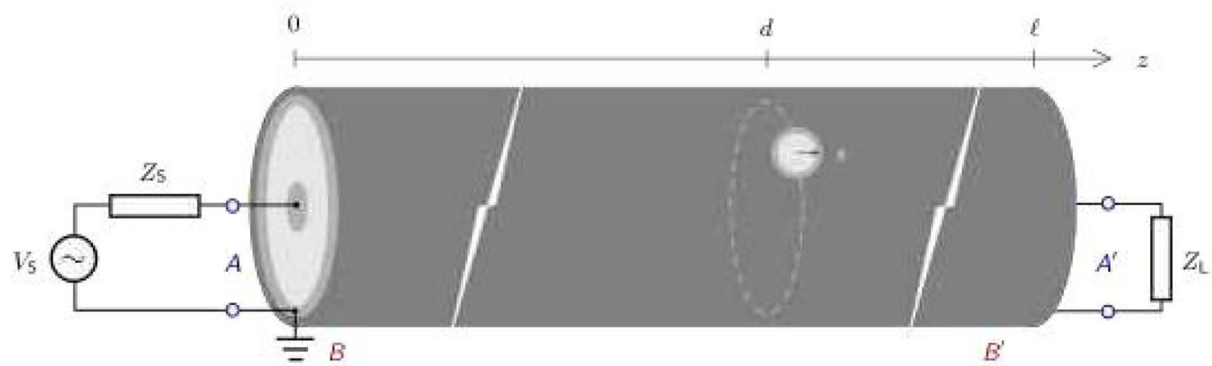


1. Just because something can’t be seen by eye does not mean it is not there!
2. Just because something is there does not mean it is important!

Physics-based mathematical models can pull us up out of the squiggly line syndrome and provide a rigorous reference for instrumentation specification.

Largest source of noise for high-frequency interrogation is cable quality

Physics Based Modeling



- Developed a two-parameter model for the TDR signature caused by a hole in the shield of a coaxial wire
  - Includes modeling for **arbitrary** interrogation signals, source/load impedance mismatch, and material properties
  - Forward model function can be evaluated in milliseconds
  - Average residual error is roughly 0.5 mV
- Enables the ability to **estimate** the distance and size of the fault based solely on the TDR response.

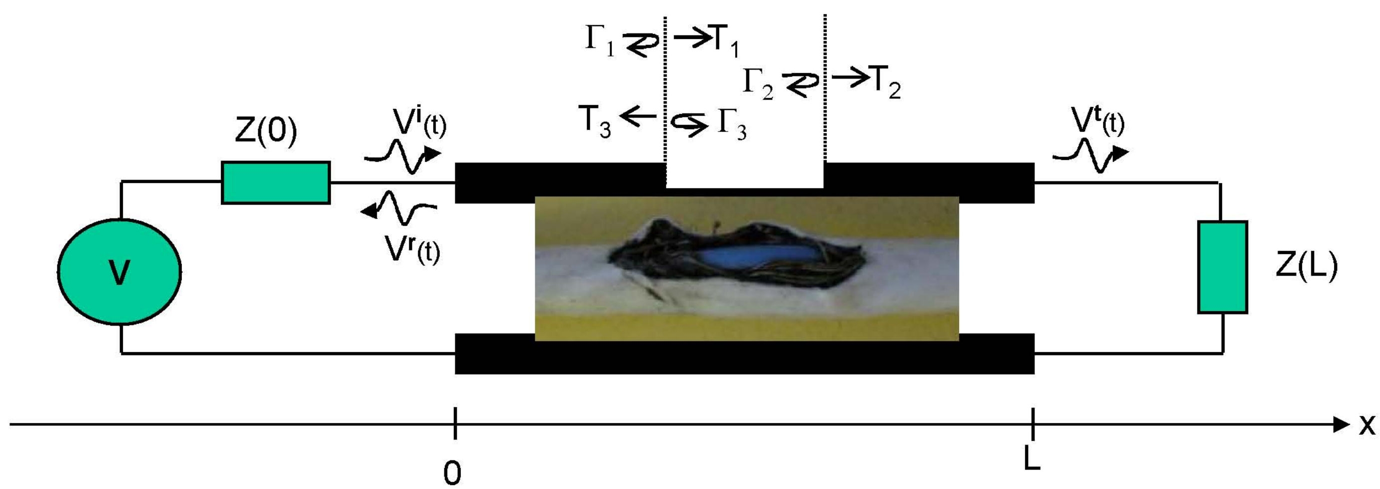
Why use Bayesian probability theory for wire faults?

Want to *infer* variables of interest from noisy reflected electrical signals:

- fault location(s)
- size of fault(s)

Want to automatically cope with sources of uncertainty:

- electrical noise from equipment and environment
- unknown or uncertain cable parameters such as permittivity, velocity of propagation, conductivity…
- geometric distortions (bends, wiggles)
- other (possibly unknown) reflection sources (such as splices)
- unknown number of possible faults (multiple faults can mix together)

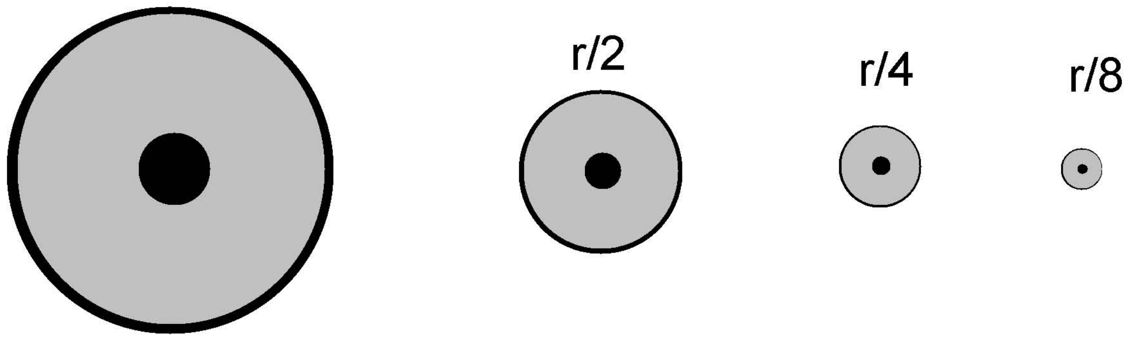


Approach

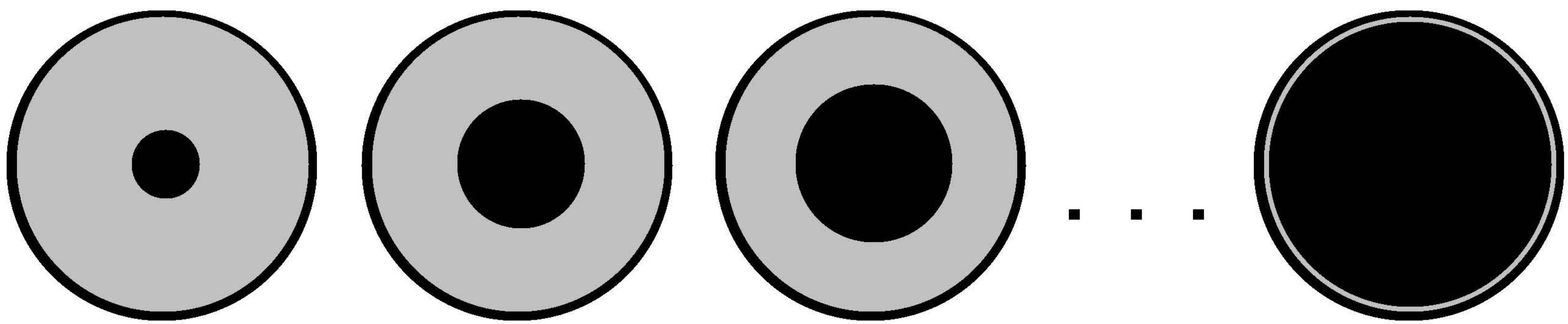
- Coaxial cable (RG-58/U AWG 20) with various size and shape holes simulated in COMSOL FEM RF simulator in frequency domain.
- Numerical integration of fields in hole calculated to measure reflection.
- Key parameters varied include: frequency, radius of curvature, distance to core conductor, hole shape & size
- Results compared with theory.

Theory vs. Reality

Radius of curvature: r, r/2, r/4, r/8

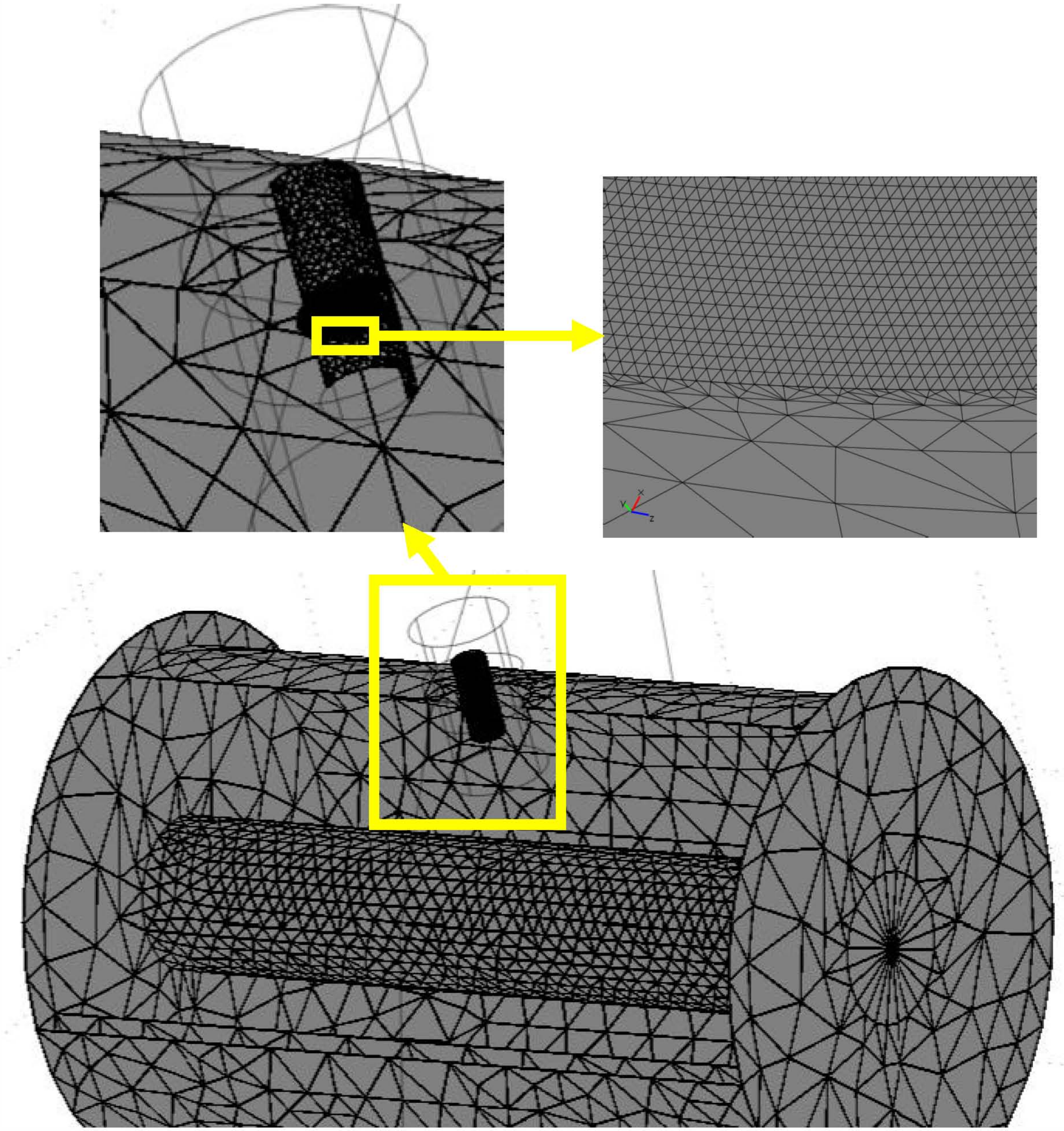


Distance to conductor: core radius 450um, 850um, 1050um, 1250um, 1350um, 1400um



Finite conductivity – Only affects calculations within hole, since hole is small, not noticeable

Comsol Coaxial Model



Mesh Statistics:

- BC Mesh 2e-7m
- 20 Million DOF
- 32 Million Elements

Geometry RG-58:

- 450um conductor radius
- 1450um inner shield radius
- permittivity 2.3
- conductance 6e7

Frequency sweep:
1GHz – 64GHz

Field in Hole

Integral of tangential field in hole (numerically integrated in COMSOL):

$$\Omega^{\pm}(h) = \int_0^{2\pi}\int_0^{s} \hat{\mathrm{v}} \cdot \mathrm{E}_{\tan}(r,\theta,\omega)\mathrm{e}^{\pm \mathrm{ih}(\mathrm{d}+\mathrm{r}\sin\theta)} r\,\mathrm{d}r\,\mathrm{d}\theta$$

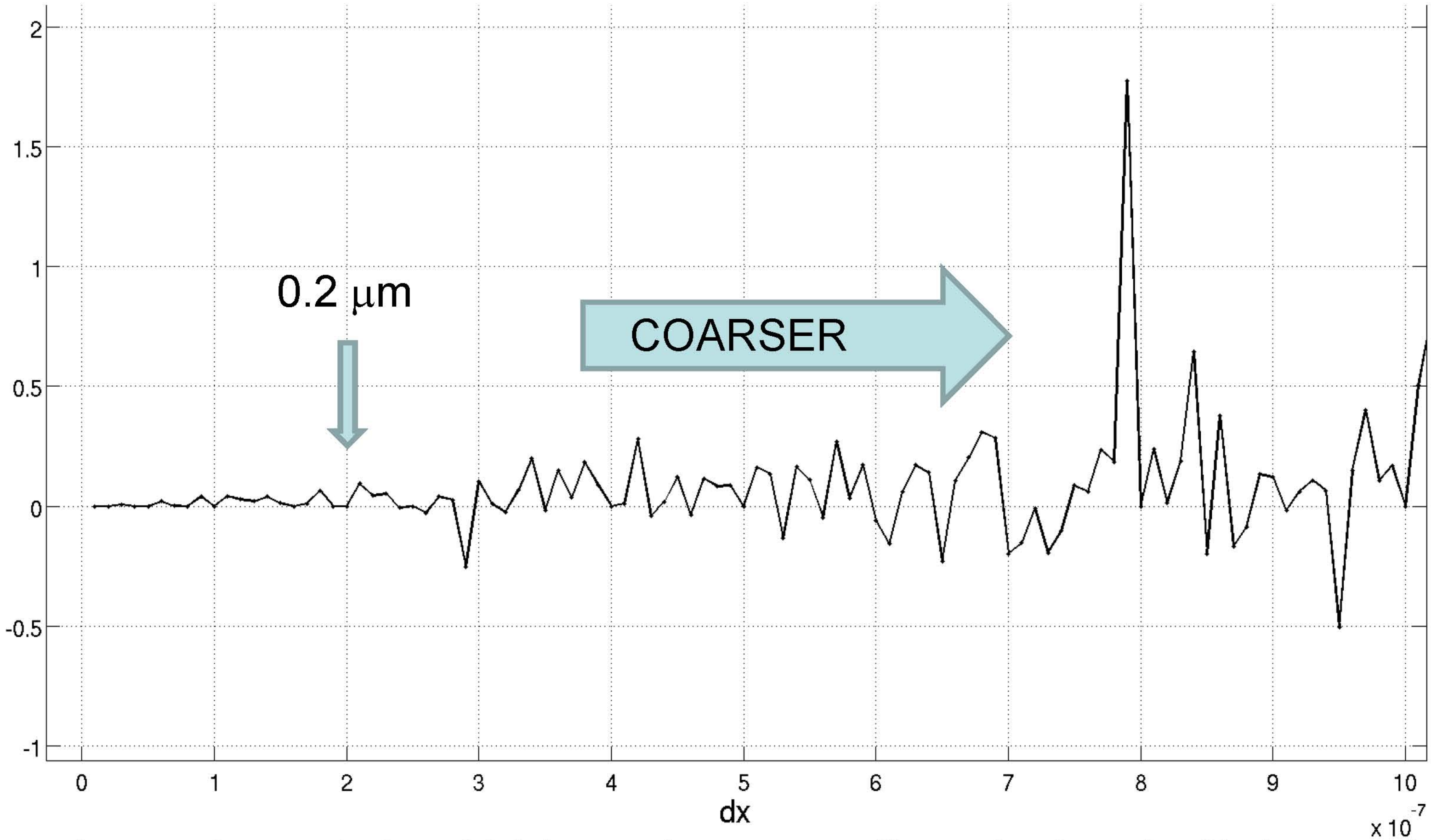
Analytic approximate solution (for comparison):

$$\approx \frac{\mathrm{i}4h\mathrm{s}^3}{3}\left[\frac{2\omega\mu_i}{h}\frac{\mu_a}{\mu_i+\mu_a}H_0(0,\omega) \pm \frac{\varepsilon_i}{\varepsilon_i+\varepsilon_a}E_0(0,\omega)\right]\mathrm{e}^{\pm \mathrm{i}hd}$$

Reflection magnitude/Frequency response:

$$\Gamma_{\mathrm{hole}} = -\frac{\mathrm{i}\omega\sqrt{\mu_i\varepsilon_i}\,s^3}{3\pi\, r_i^2 \ln(r_i / r_c)}\left(\frac{2\mu_a}{\mu_i+\mu_a}+\frac{\varepsilon_i}{\varepsilon_i+\varepsilon_a}\right)\mathrm{e}^{\mathrm{i}2hd}$$

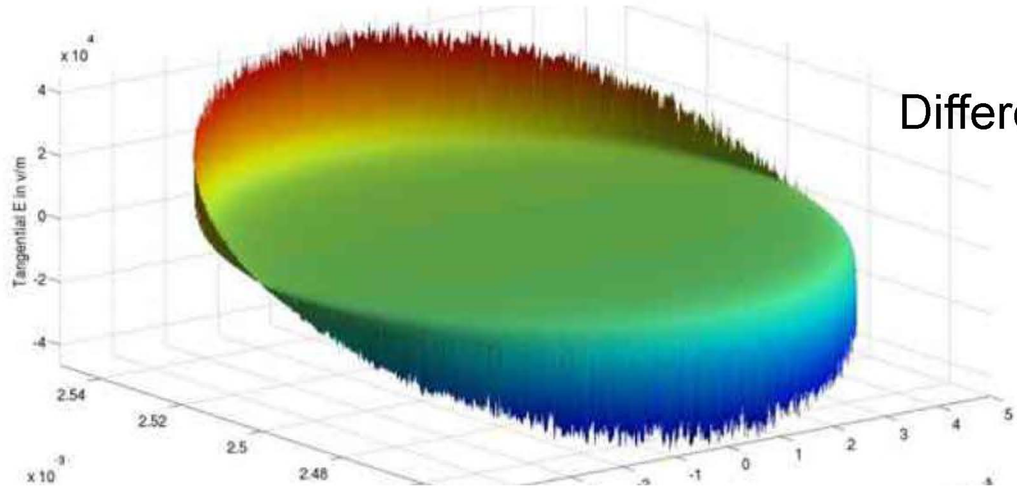
Spatial Requirements of Numerical Integration of Ω



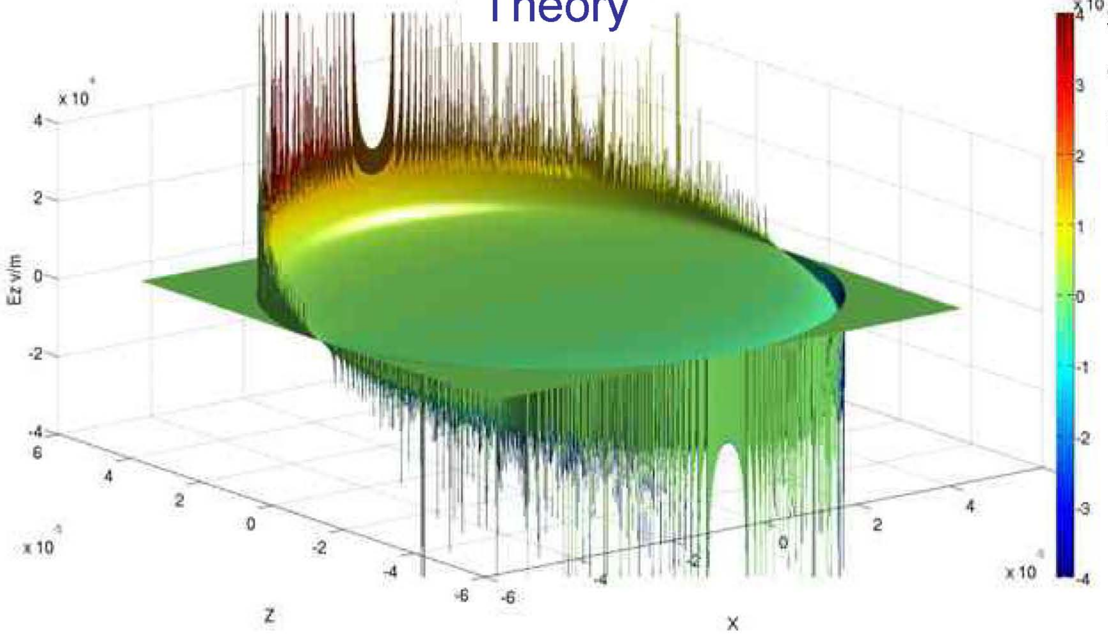
- As mesh resolution (dx) is made coarser (from 1e-8 to 1e-6) the resulting numerical integration becomes inconsistent.
- From this graph the coarsest suitable mesh spacing is $2e^{-7}$m.
- Required resolution is 4 orders of magnitude finer then the Courant requirement for coax at 60GHz.

Tangential E Fields

Comsol



Theory

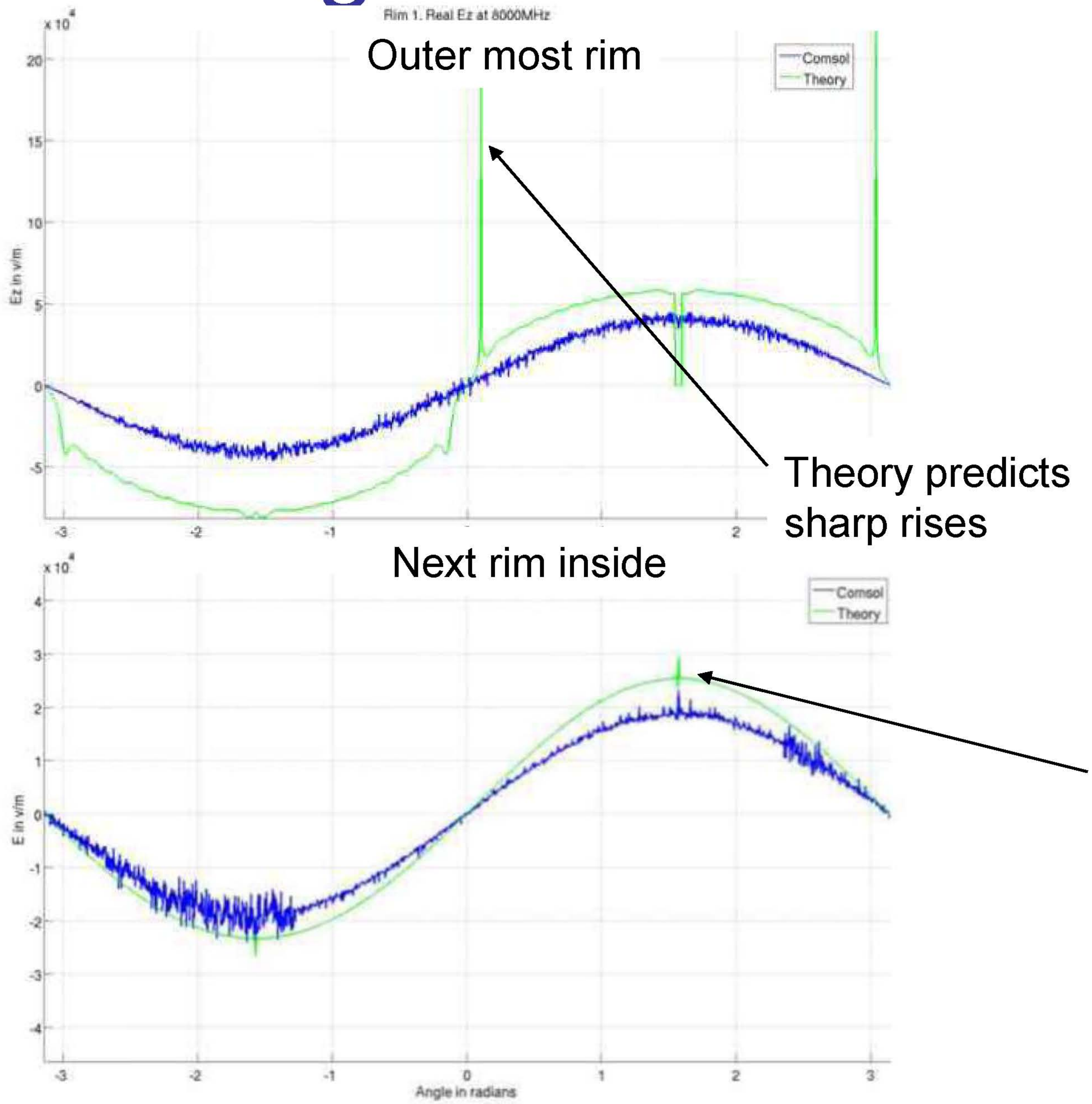


50um hole at 8GHz

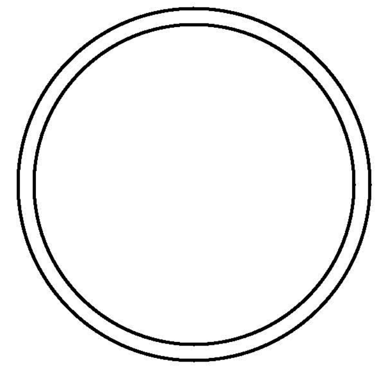
Differences between simulation and theory

- simulation has physical Shield on coaxial cable, theory has b.c. on plane
- simulation is finite, theory's fields can go towards infinity,
- simulation limited to 2e-7m spatial resolution
- Comsol is coaxial and theory is planar.

Tangential E Profiles Radially



Discontinuity artifact from non-uniform meshing

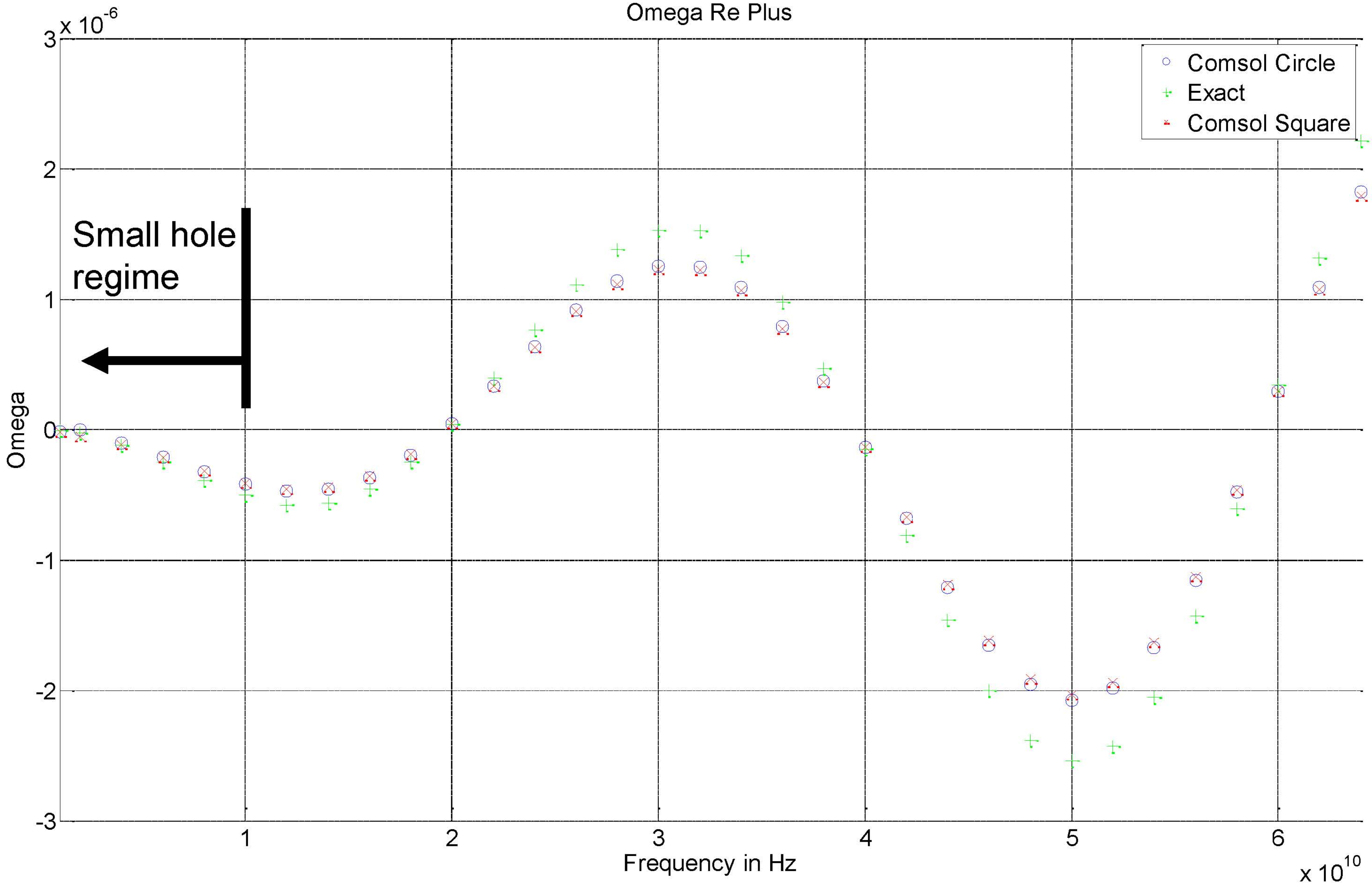


Circular profiles of fields separated by 2um from edge of 50um hole.

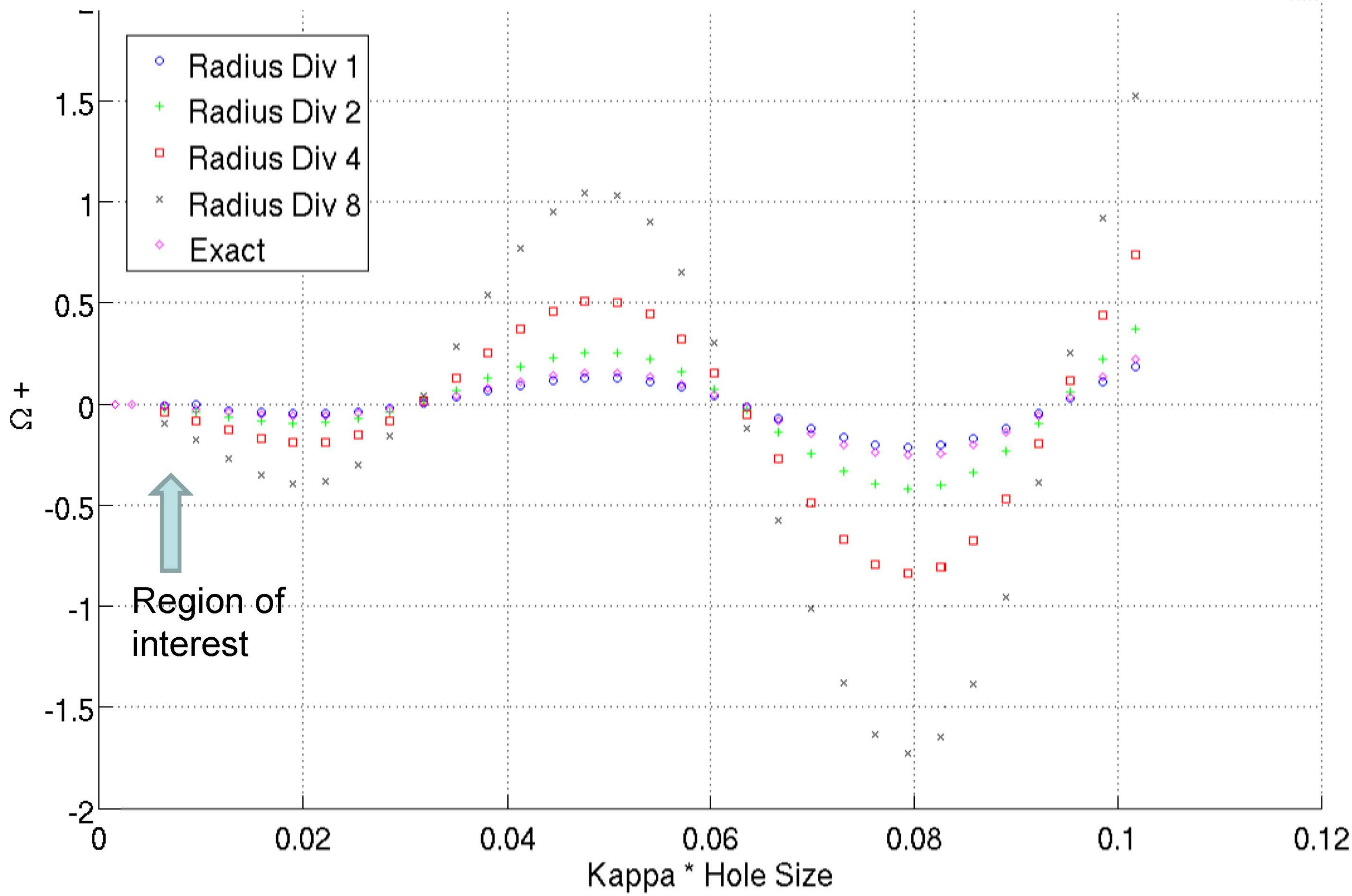
Frequency Response

- In standard time-domain reflectometry, the time domain reflection coefficient has max and min values per short and open circuit conditions.
- This frequency domain reflection coefficient has a different range.
- To establish normalized range, the biggest reflection case is define as resulting from biggest possible shield hole at source (e.g. radius of hole is radius of shield).

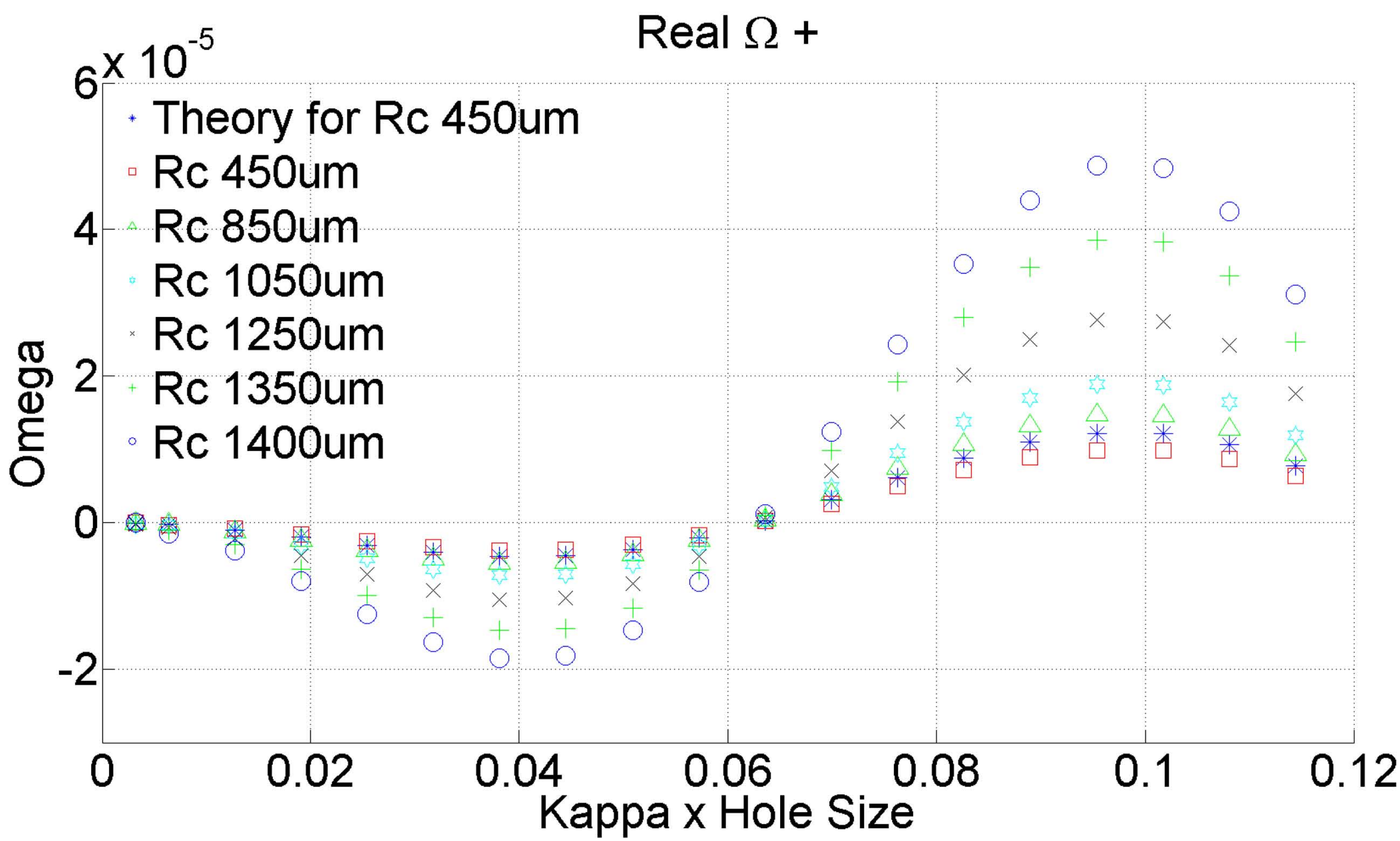
Real Ω+, 50μm hole
Effects of Shape



Real Ω+
Effects of Curvature



Distance to Conductor



Trade-space

Fault Variables
- hole size
- distance to fault from source
- rate of chafing (hole growth)
- hole shape
- radial location
- number of faults

Measurement Variables
- reflection magnitude
- transmission magnitude
- S-parameters

Extrinsic Variables
- interrogation frequencies
- wave shapes
- voltages and currents
- load requirements

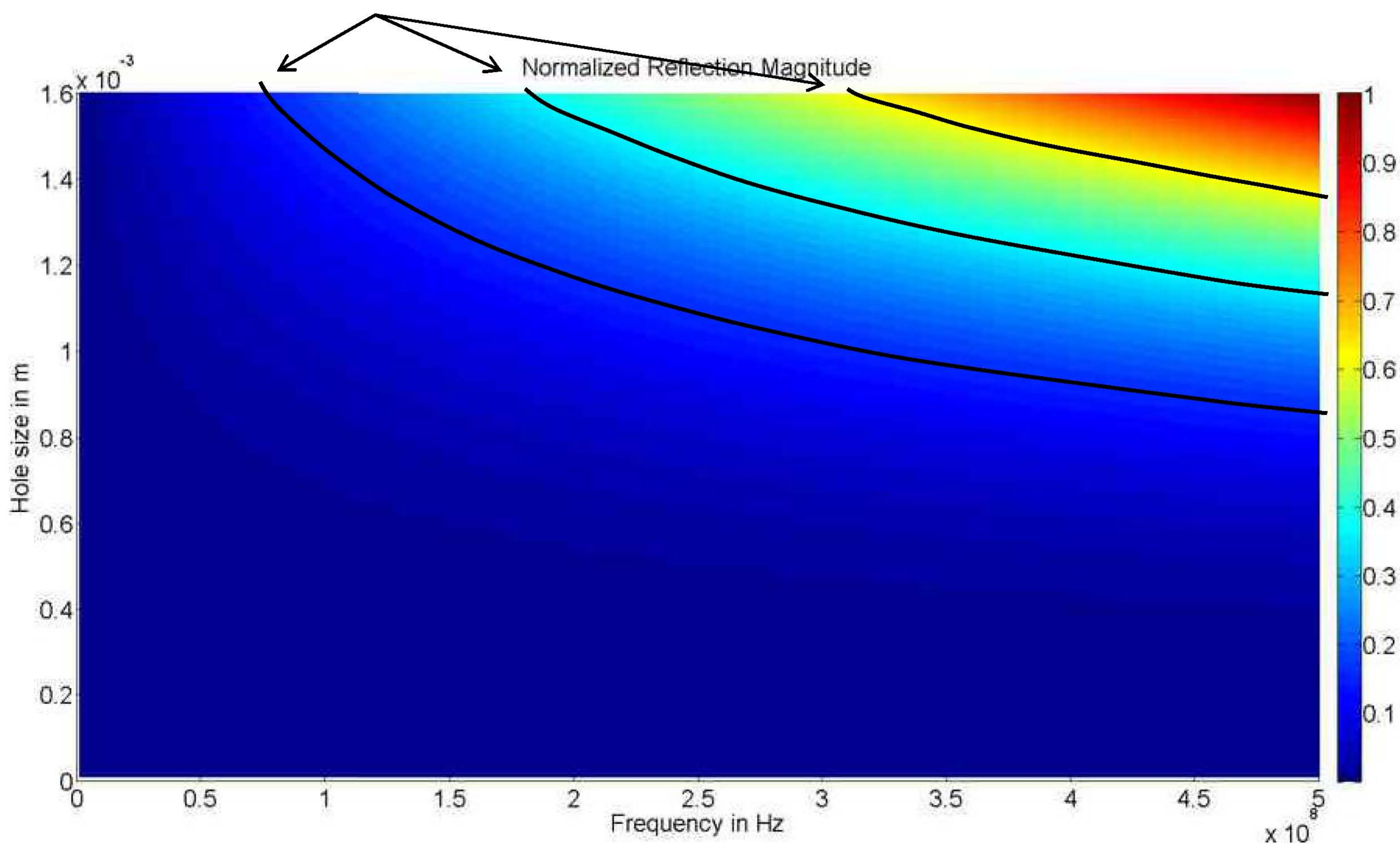
Intrinsic Variables
- conductivity, permittivity, permeability
- geometries (radiis)
- configuration (coaxial, twisted, …)
- cable length
- cable quality (the squiggles)

Trade-space

Normalized reflection magnitude as a function of frequency and hole size

(Normalized by magnitude of max reflection of biggest hole (shield radius) at source).

Possible instrument dynamic range limit curves

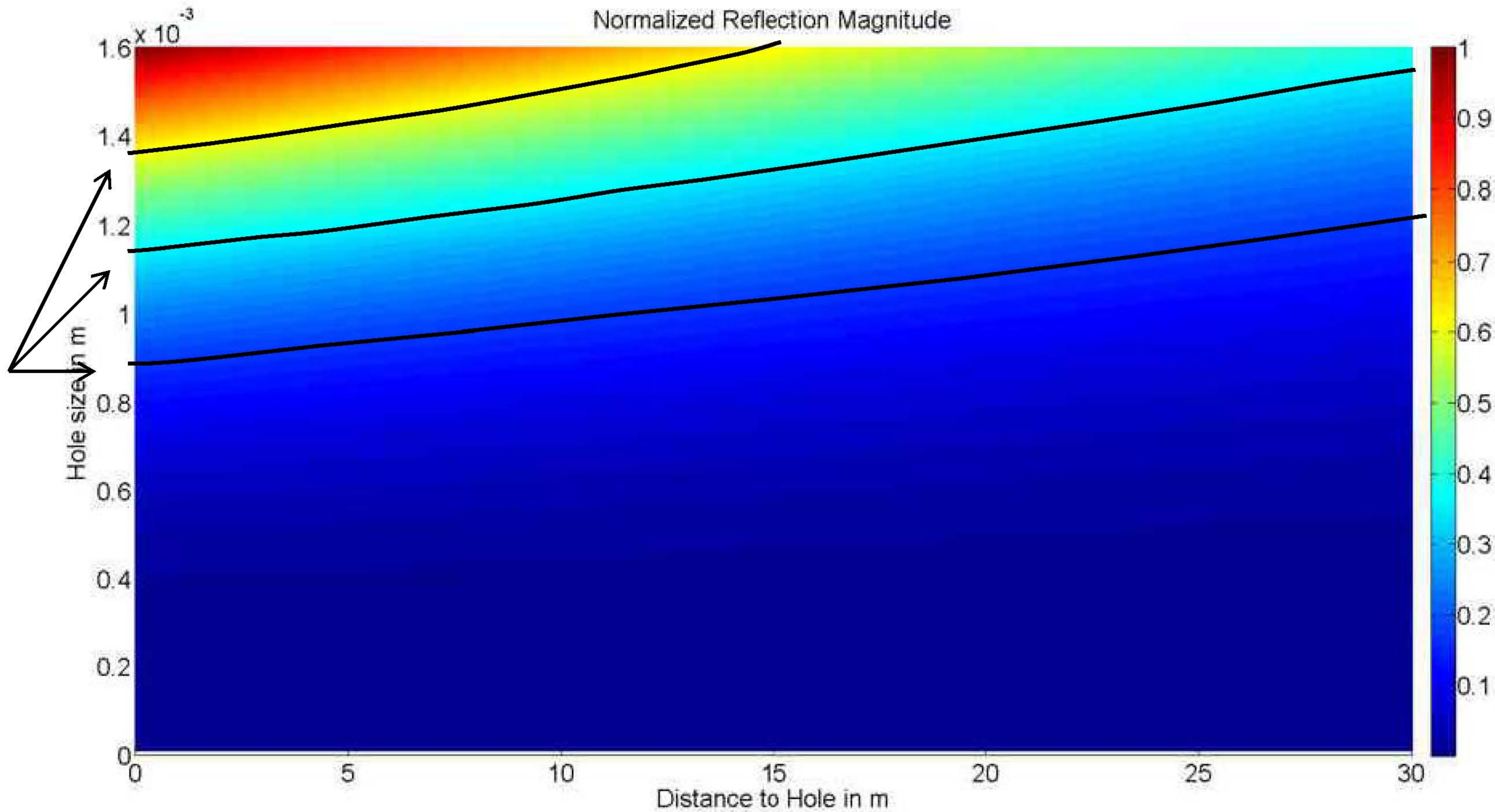


Trade-space

Reflection magnitude as a function of distance to fault and hole size

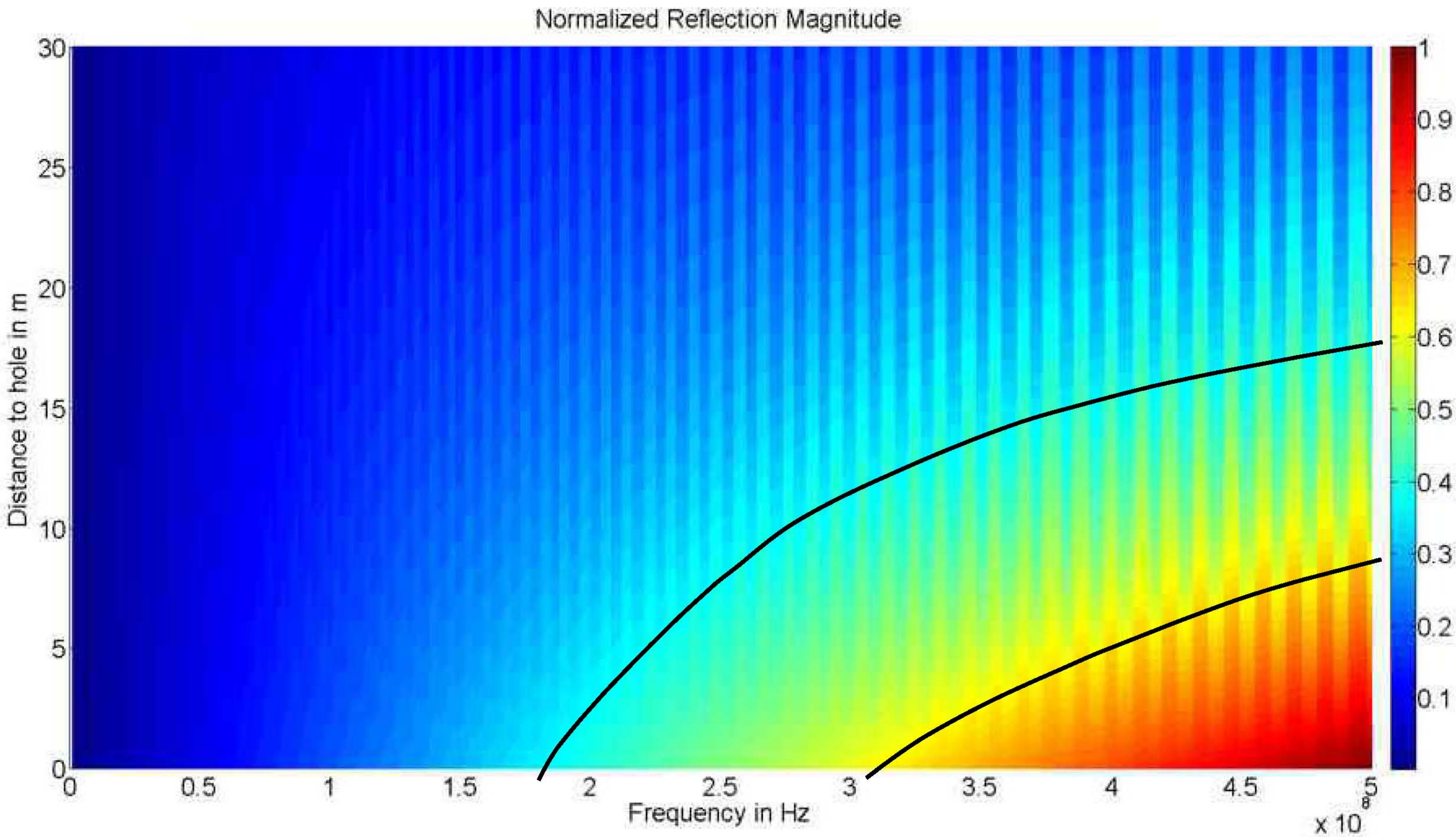
Frequency = 250 MHz

Possible instrument dynamic range limit curves



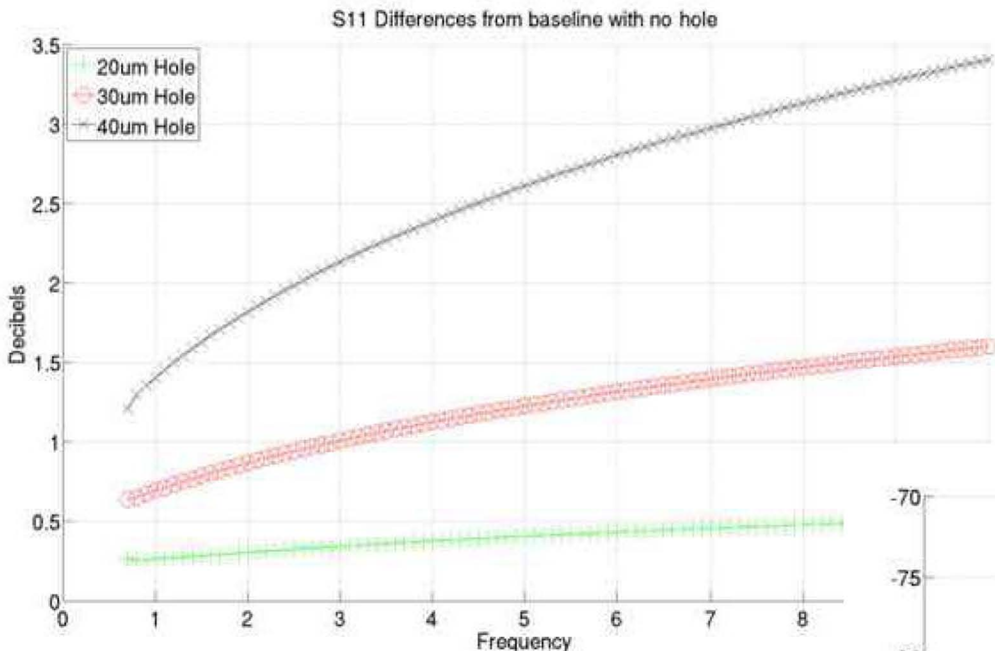
Trade-space

Reflection for a fixed hole size of 0.5 mm as a function of frequency and distance to fault

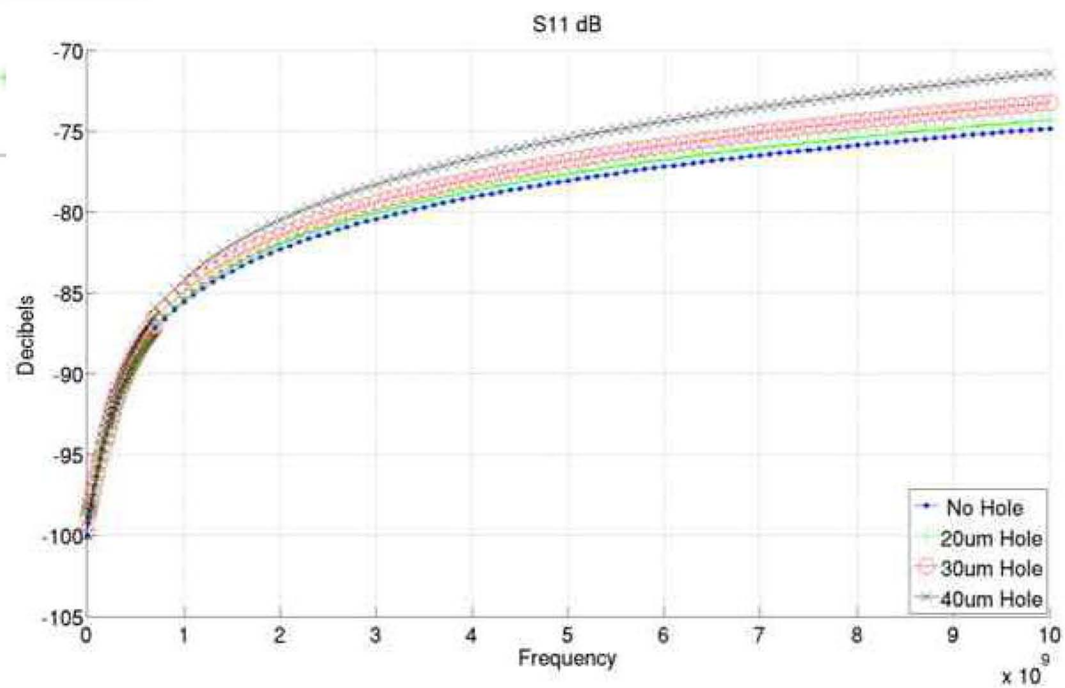


Trade-space

S11 for coaxial cable as area of holes change



- Hole area has broad spectral response.
- Double area results in 0.5dB at 1GHz and 3.0dB reflection at 10GHz.



- Higher frequencies result in better small hole detection.
- Higher frequencies propagate less distance.

Trade-space

Cable Quality as a limit for noise floor/dynamic range

Higher frequencies (gigahertz) have stronger reflections on imperfections:

1. Shield weave variations
2. Shield longitude conductivity variations
3. Roughness of conductors
4. Geometry variations from manufacturing – especially important to STP
5. Connector pin length variations

Summary

- Small hole theory is valid for shielding chafe holes in coaxial cable in small hole regime (kappa * hole size) < 0.01.
- Hole shape does not affect omega integral with equal area holes.
- As long as chafe hole size is small with respect to radius of coax curvature effects are negligible.
- Trade-space for fault detection in coaxial cables has been outlined.

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